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13. ABSTRACT *(Maximum 200 words)*

The problem of guaranteeing safety in a class of robot motion problems has been studied. Necessary and sufficient conditions for ensuring safety have been determined. Functional relationships between the number, size, and speed of obstacles and the robot's maximum speed to ensure safety have been developed.

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AFOSR Grant No. F49620-93-1-0065
Final Report
Logic-based Real Time Problem Solving Systems

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1. OBJECTIVES:

The primary aim of this research is to study the theory and implementation of *logic-based*, multi-agent, real-time artificial intelligence systems. Though logic-based computational techniques have exhibited poor run-time performance in the past, the recent Nerode-Subrahmanian project on fast, incremental logical computations based on mixed integer linear programming techniques shows promise of being able to overcome many of the previous drawbacks of logic-based systems. In this proposal, we have studied techniques for incremental real-time logic based computations for a variety of artificial intelligence applications such as fast logical inference, reasoning with uncertainty, planning, planning with uncertainty, and high performance knowledge bases.

2. STATUS OF EFFORT: A brief statement of progress towards achieving the research objectives. (Limit to 200 words).

AFOSR funding for this project began in Dec. 1992. The project centered on developing techniques to integrate planning, logical reasoning and numerical reasoning methods for real-time applications. Towards this end, Subrahmanian has worked, jointly with Nerode, on the development of a software architecture called Hybrid Knowledge Systems that allow for the seamless integration of numerical techniques, logical reasoning techniques, and AI techniques. Hendler and Subrahmanian have developed techniques linking planning to logical reasoning. In addition, new work is examining other approaches to scaling AI by use of High Performance Computing techniques and the use of constraint-based techniques for interoperability of multiple datasources and reasoning paradigms.

Effort was completed and funds expended as of August, 1996.

3. ACCOMPLISHMENTS/NEW FINDINGS: Describe research highlights, their significance to the field, their relationship to the original goals, their relevance to the AF's mission, and their potential applications to AF and civilian technology challenges.

- (Fast and Scalable Inference Techniques)

  1. Query processing in *ground* definite deductive databases is known to correspond precisely to a linear programming problem. However, the "groundedness" requirement is a huge drawback to using linear programming techniques for logic program computations because the ground version of a logic program can be very large when compared to the original logic program. Furthermore, when we move from propositional logic programs to first order logic programs, this effectively means that functions symbols may not occur in clauses. In this work, we develop a theory of "instantiate-by-need" that performs instantiations (not necessarily ground instantiations) only when needed. We prove that this method is sound and complete when computing answer substitutions for non-ground logic programs including those containing function symbols. More importantly, when taken in conjunction with Colmerauer's result that unification can be viewed as linear programming, this means that resolution with unification can be completely replaced by linear programming as an operational paradigm. Additionally, our tree construction method is not rigidly tied to the linear programming paradigm – we will show that given any method M (which some implementors may prefer) that can compute the set of atomic logical consequences of a propositional logic program, our method can use M to compute (in a sense made precise in the work), the set of all (not necessarily ground) atoms that are consequences of a first-order logic program.
  2. Unlike sets of definite Horn clauses, logic programs with disjunctions of atoms in clause heads are often interpreted in terms of minimal models. It is also well known that the minimal models of logic programs are closely related to the so-called stable models of logic programs with non-monotonic negation in clause bodies, as well as to circumscription. Methods to compute minimal models of logic programs are becoming increasingly important as an intermediate step in the computation of structures associated with nonmonotonic logic programs. However, to date, all these techniques have been restricted to the case of *propositional* logic programs which means that an ordinary disjunctive logic program must be "grounded out" prior to computation. Grounding out in this manner leads to a combinatorial explosion in the number of clauses, and hence, is unacceptable. In this work, we show how, given any method M which correctly computes the set of minimal models of a propositional logic program, we can develop a strategy to compute truth in a minimal model of a disjunctive logic program P. The novel feature of our method is that it works on an "instantiate-by-need" basis, and thus avoids unnecessary grounding.
  3. The declarative semantics of nonmonotonic logic programming has largely been based on propositional programs. However, the ground instantiation of a logic program may be very large, and likewise, a ground stable model may also be very large. We develop a non-ground semantic theory

for nonmonotonic logic programming. Its principal advantage is that stable models and well-founded models can be represented as sets of atoms, rather than as sets of ground atoms. A set SI of atoms may be viewed as a compact representation of the Herbrand interpretation consisting of all ground instances of atoms in SI. We develop generalizations of the stable and well-founded semantics based on such non-ground interpretations SI. The key notions for our theory are those of *covers* and *anticovers*. A cover as well as its anticover are sets of substitutions—non-ground in general—representing all substitutions obtained by ground instantiating some substitution in the (anti)cover, with the additional requirement that each ground substitution is represented either by the cover or by the anticover, but not by both. We develop methods for computing anticovers for a given cover, show that membership in so-called optimal covers is decidable, and investigate the complexity in the Datalog case.

4. Turi introduced the important notion of a constrained atom: an atom with associated equality and disequality constraints on its arguments. A set of constrained atoms is a constrained interpretation. We show how non-ground representations of *both* the stable model semantics and the well-founded semantics may be obtained through Turi's approach. The practical implication of this is that the well-founded model (or the set of stable models) may be partially pre-computed at compile-time, resulting in the association of each predicate symbol in the program to a constrained atom. Algorithms to create such models are presented, both for the well founded case, and the case of stable models. Query processing reduces to checking whether each atom in the query is *true* in a stable model (resp. well-founded model). This amounts to showing the atom is an instance of one of some constrained atom whose associated constraint is solvable. Various related complexity results are explored, and the impacts of these results are discussed from the point of view of implementing systems that incorporate the stable and well-founded semantics.

- **(Planning with Uncertainty and Incompleteness)**

1. In this work, we examine how the complexity of domain-independent planning with STRIPS-style operators depends on the nature of the planning operators.

   We show conditions under which planning is decidable and undecidable. Our results on this topic solve an open problem posed by Chapman and clear up some difficulties with his undecidability theorems.

   For those cases where planning is decidable, we show how the time complexity varies depending on a wide variety of conditions:

   - whether or not function symbols are allowed;
   - whether or not delete lists are allowed;
   - whether or not negative preconditions are allowed;

- whether or not the predicates are restricted to be propositional (i.e., 0-ary);
- whether the planning operators are given as part of the input to the planning problem. or instead are fixed in advance.
- whether or not the operators can have conditional effects.

Furthermore, we provide insights about the reasons for our results.

2. formalizations for problems involving actions remains one of the main application challenges of non-monotonic knowledge representation. In this work, we show that complex planning strategies find natural logic-based formulations and efficient implementations in the framework of deductive database languages. We begin by modeling classical STRIPS-like totally ordered plans by means of $Datalog_{1S}$ programs, and show that these programs have a stable model semantics that is also amenable to efficient computation. We then show that the proposed approach is quite expressive and flexible, and can also model partially ordered plans, which are abstract plans whereby each plan stands for a whole class of totally ordered plans. This results in a reduction of the search space and a subsequent improvement in efficiency. iWe further illistrate that the above pproach is quite expressive and flexible. and can also be employed to model parallel plans, where several actions can be executed simultaneously. The characterization of parallel plans as abstract (partially ordered) plans also allows us to reduce the search space and hence to improve the efficiency of the planning process.
3. We present a formal model for reasoning about probabilistic information in STRIPS style planning. We then show that all probabilistic planning problems expressible in this model may be represented as equivalent probabilistic logic programs. yielding a sound and complete method for finding such plans.

- (Guaranteed Safety) "Mission-critical" systems, which include such diverse applications as nuclear power plant controllers, "fly-by-wire" airplanes, medical care and monitoring systems. and autonomous mobile vehicles, are characterized by the fact that system failure is potentially catastrophic. The high cost of failure justifies the expenditure of considerable effort at design-time in order to guarantee the correctness of system behavior. We examined the problem of guaranteeing safety in a well studied class of robot motion problems known as the "asteroid avoidance problem." We established necessary and sufficient conditions for ensuring safety in the simple version of this problem which occurs most frequently in the literature, as well as sufficient conditions for a more general and realistic case. In doing so. we established functional relationships between the number, size and speed of obstacles, the robot's maximum speed and the conditions which must be maintained in order to ensure safety.

- (Other Applications) Though numerous multimedia systems exist in the commercial market today, most development efforts have proceeded along ad-hoc

lines that apply in narrow domains. In this work, we propose certain central principles around which multimedia database systems (for a variety of applications) may be uniformly built in a domain-independent fashion. The principles can be implemented as a shell/compiler to which can be added, domain-specific components that may vary from application to application. We show that for most media data existing today, it is possible to build some meta-data "on top" of that physical medium. This meta-data may be generated by a human being, or by an image processing program, or by a combination of the two, and may involve various degrees of certainty/reliability. This meta-data may then be queried using a unified logical query language. The language has a well-understood syntax and semantics rooted in formal logic. Based on this formal model, we have developed a prototype implementation of a system called MACS (for "Media-Abstraction Creation System") that provides the shell facilities alluded to above. In parallel, Subrahmanian has been developing a general-purpose framework called HERMES for integrating diverse forms of information using the concept of a mediator. We have shown how MACS and HERMES jointly provide efficient support for multimedia reasoning with access to heterogeneous data sources. A structured multimedia database system imposes a certain mathematical structure on the set of features/states. Using this notion of a structure, we are able to define indexing structures for processing queries, methods to relax queries when answers do not exist to those queries, as well as sound, complete and terminating procedures to answer such queries (and their relaxations, when appropriate). We show how a media-presentation can be generated by processing a sequence of queries, and furthermore we show when these queries are extended to include constraints, then these queries can not only generate presentations, but also generate temporal synchronization properties and spatial layout properties for such presentations. We describe the architecture of a prototype multimedia database system based on the above principles.

4. Personnel Supported:

List professional personnel (Faculty, Post-Docs, Graduate Students, etc.) supported by and/or associated with the research effort.

VS Subrahmanian
James A. Hendler
Robert Kohout, graduate student
David Rager, faculty research assistant
Charles Ward, Graduate Student
Sibel Adali, Graduate Student
K.S.Candan, Graduate Student

5. Publications:

Published:

1. J. Hendler, K. Stoffel and A. Mulvehill High Performance Support for Case-Based Planning Applications, in A. Tate (ed) "Advanced Planning Technology,"

MIT/AAAI Press, Menlo Park. CA., USA. May 1996

2. J. Hendler, Types of Planning — can artificial intelligence yield insights into prefrontal function? in Boller and Grafman (eds.) "The Frontal Lobes – Annals of the New York Academy of Science" Vol 769, 1995

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5. R. Kohout. J. Hendler and D. Musliner) "Guaranteeing Safety in Spatially Situated Agents", "HTN Planning: Complexity and Expressivity" Proc. 13th Natl. Conf. on Artificial Intelligence (AAAI-96). Portland, OR August 1996.

6. R. Tsuneto, K. Erol. J. Hendler. D. Nau. "Commitment Strategies in Hierarchical Task-Network Planning". Proc. Thirteenth Natl. Conf. on Artificial Intelligence (AAAI-96)", Portland. OR August 1996.

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13. S. Marcus and V.S. Subrahmanian. Foundations of Multimedia Database Systems, JOURNAL OF THE ACM, Vol. 43. 3, pps 474–523, 1996.

14. C. Bell, A. Nerode, R. Ng and V.S. Subrahmanian. Implementing Deductive Databases by Mixed Integer Programming. ACM TRANSACTIONS ON DATABASE SYSTEMS, vol. 21, nr. 2,

15. V. Kagan, A. Nerode and V.S. Subrahmanian. Computing Minimal Models by Partial Instantiation. THEORETICAL COMPUTER SCIENCE, vol. 155, pps 157–177.

16. S. Adali and V.S. Subrahmanian. Amalgamating Knowledge Bases, III: Algorithms, Data Structures and Query Processing. JOURNAL OF LOGIC PROGRAMMING, Vol 28(1), pps 57-100. July 1996.

17. The PARK Semantics for Active Rules, in: *Proc. 1996 Intl. Conf. on Extending Database Technology*, Avignon. France. March 1996. (with G. Gottlob and G. Moerkotte).

18. Secure Mediated Databases. in: *Proc. 1996 Intl. Conf. on Data Engineering*, Feb. 1996, New Orleans. LA. (with K.S. Candan and S. Jajodia).

19. Query Processing in Distributed Mediated Systems. in: *Proc. 1996 ACM SIGMOD Conf. on Management of Data*. Montreal. Canada. June 1996. (with S. Adali. K.S.Candan and Y. Papakonstantinou).

20. Towards a Theory of Collaborative Multimedia. Proc. 1996 IEEE Multimedia Systems Conference, pps 279–283. Hiroshima. Japan. June 1996.

21. A Deductive Database Approach to Planning in Uncertain Environments. Proc. 1996 Intl. Workshop on Logic in Databases, San Miniato. Italy, July 1-2, 1996. (with Charlie Ward).

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23. J. Lu. A. Nerode and V.S. Subrahmanian. Hybrid Knowledge Bases. IEEE TRANSACTIONS ON KNOWLEDGE AND DATA ENGINEERING. S. 5. pps 773–785, Oct. 1996.

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25. G. Gottlob, S. Marcus. A. Nerode. G. Salzer and V.S. Subrahmanian. A Non-Ground Realization of the Stable and Well-Founded Semantics. THEORETICAL COMPUTER SCIENCE, vol. 166. Nr. 1/2. pps 221-262. Oct.1996.

26. P. Bonatti, M.-L. Sapino and V.S. Subrahmanian. (1996) *Merging Heterogeneous Security Orderings*, Proc. European Symposium on Research in Computer Security (ESORICS), Sep. 1996. Springer LNCS Vol. 1146, pps 183–197.

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28. V.S. Subrahmanian and C. Zaniolo. Relating Stable Models and AI Planning Domains, accepted for publication in: *Proc. 1995 Intl. Conf. on Logic Programming*, Tokyo, Japan.

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Accepted but not yet published:

1. O. Seeliger and J. Hendler Supervenient Hierarchies of Behaviors in Robotics, "Journal of Experimental and Theoretical AI." (Accepted for Publication 1995).

2. K. Erol. J. Hendler and D. Nau Complexity Results for Hierarchical Task-Network Planning, "Annals of Mathematics and Artificial Intelligence." (Accepted for Publication. 1995).

3. S. Pradhan. J. Minker and V.S. Subrahmanian. Combining Databases with Prioritized Information. accepted for publication in:

4. A. Brogi, V.S.Subrahmanian and C. Zaniolo. The Logic of Total and Partial Order Plans: A Deductive Database Approach. accepted for publication in: ANNALS OF MATH AND ARTIFICIAL INTELLIGENCE.

5. K.S. Candan. J. Grant and V.S. Subrahmanian. A Unified Treatment of Null Values using Constraints. Accepted for publication in: INFORMATION SCIENCE journal.

6. A. Dekhtyar and V.S. Subrahmanian. (1997) *Hybrid Probabilistic Progrms*, accepted for publication in: *Proc. 1997 Intl. Conf. on Logic Programming*, Leuven, Belgium. July 8-12. 1997.

6. Interactions/Transitions:

a. Participation/presentations at meetings. conferences. seminars. etc.

Dr. Subrahmanian and Dr. Hendler have participated in or given presentations at more than 75 locations during the grant period.

b. Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories. Provide factual information about the subject matter, institutions, locations, dates. and name(s) of principal individuals involved.

PROF. J. HENDLER:

Professor Hendler is a member of the prestigious IDA Defense Science Study Group – a selected group of fifteen young scientists from across all disciplines of science who are exposed to the DoD S&T process via briefings. visits and consultive meetings. Recent meetings have included the following individuals (as well as many others):

Rear Admiral C. Beers. USN Commander SWFLANT (Aug 1996) Rear Admiral William Fallon, USN - DCINCLANTFLT (Aug 1996) Brig Gen T. Goslin, USAF, 509

Bomb Wing, Whiteman AFB (June 1996) General E. E. Habinger, USAF - CINC-STRAT (June 1996) Helmut Hellwig, Deputy Asst Secy, US Air Force (Feb 1996) Lt General J.Keane, USA, Commanding General XVIII Airborne (Aug 1996) Lt General W. Kross, USAF, Director, Joint Staff (Feb 1996) Major General J. McCombs, USAF, DCINC, USSOCOM (Aug 1996) Maj. Gen R. Paul, USAF, DCINC (S&T) AFMCC (June 1996) Gen J. H. B. Peay, USA, CINC USCENTCOM (Aug 1996) Col. R. Sayers, VC Air Warfare Ctr. Nellis AFB (June 1996) General J. Shalikashvili, Chair US Joint Chiefs of Staff (Feb 1996) General John Sheehan, USMC, CINC USACOM (Aug 1996) Lt. Gen H. Smith, USAF, USTRANSCOM (June 1996) Gen. H. Viccellio, USAF, CINCAFMCC (June 1996) Lt General C. Wilhelm, USMC, Commander MARFORLANT (Aug 1996)
Accompanying the DSSG on our trips have been: Gen (ret) L. Welch Gen (ret) W. Smith Adm (ret) H. Train
A report on the meetings with the above and other USAF and military personel has been separately provided to the AFOSR (Dr. Abe Waksman).
In addition, Professor Hendler is working on a report on "Information Technology in Weapons System acquisition" for General Welch, a member of the Defense Science Board.

PROF V.S. SUBRAHMANIAN: Prof. Subrahmanian has worked extensively with the US Army Topographic and Engineering Center (TEC, John Benton POC), and the US Army CECOM (T. Cronin, POC). See item (c) below for more details.

c. Transitions. Describe cases where knowledge resulting from your effort is used, or will be used, in a technology application. Transitions can be to entities in the DOD, other federal agencies, or industry. Briefly list the enabling research, the laboratory or company, and an individual in that organization who made use of your research.

The ForMAT program, developed by Mitre Corporation and demonstrated at several JWID exercises, is a transportation logistics system for military use. A new version of this program is under development jointly with Mitre, BBN and the PIs of this project. The new version uses the Parka high performance knowledge representation (developed by Hendler) as its memory, and uses the Hermes mediator system (developed by Subrahmanian) to link to distributed datasources. This version is under consideration to be demoed at the upcoming JFACC "Jump Start" demonstration (with ISX). (Personnel involved: David Brown, Mitre Corp; Alice Mulvehill, BBN; J. Hendler and VS Subrahmanian, UMCP; Brian Kettler, ISX).

Prof. Subrahmanian has worked extensively with the US Army Topographic and Engineering Center (TEC, John Benton POC) on optimal siting of missile batteries for defending friendly assets. This led to algorithms that recently were shown to conclusively improve (both theoretically and practically) the quality of defenses provided to such assets. Prof. Subrahmanian has also been involved in work with U.S. Army CECOM on planning optimal fly-throughs through enemy terrain so as to optimally gather radio-frequency (RF) intelligence about enemy antennas/radar. In addition, Prof. Subrahmanian has a large scale on-going effort with IBM whereby IBM's Advanced Scout data mining software (reported on in the Washington Post, Wall Street Journal, New York Times, etc.) will be enhanced with a rich new theory

being developed by him.

7. New discoveries, inventions, or patent disclosures. (If none, report None.)

None

8. Honors/Awards: List honors and awards received during the grant/ contract period. List lifetime achievement honors such as Nobel prize, honorary doctorates, and society fellowships prior to this effort.

Professor Hendler received a ten-month Fulbright Foundation Research award for the 1995 Academic Year. This award, offered through the US-Israel Educational Foundation, will support Dr. Hendler's research in planning and robotics at Hebrew University in Jerusalem.

Professor Hendler was chosen as a member of the prestigious Defense Science Study Group by the Institute for Defense Analysis. Fifteen young American scientists, from across all fields of science, are chosen for this two year study group.

Professor Hendler was chosen as an Associate Editor for the "Journal of Experimental and Theoretical Artificial Intelligence." He was also chosen as an Editorial Board member for both "IEEE Expert" and the new journal "Autonomous Robots."

Professor Hendler was chosen as a Fellow of the Kiss Institute for Practical Robotics (KIPR). Located in Virginia, KIPR is a non-profit institute dedicated to education and research in the field of practical robotics.

Professor Subrahmanian received an NSF Young Investigator Award in 1993. Prof. Subrahmanian was chosen as an Associate Editor of the IEEE Transactions on Knowledge and Data Engineering. Prof. Subrahmanian was invited to become a member of DARPA's 6-member executive advisory council on advanced logistics. Subrahmanian delivered invited addresses at 3 conferences during the past year (Uncertainty in AI 1995, Nonmonotonic Reasoning Implementations at IJCAI 1995, Italian Database Conf. 1996) as well as served on invited panels at various prestigious conferences (IEEE Data Engineering 1996, IEEE Multimedia 1996).